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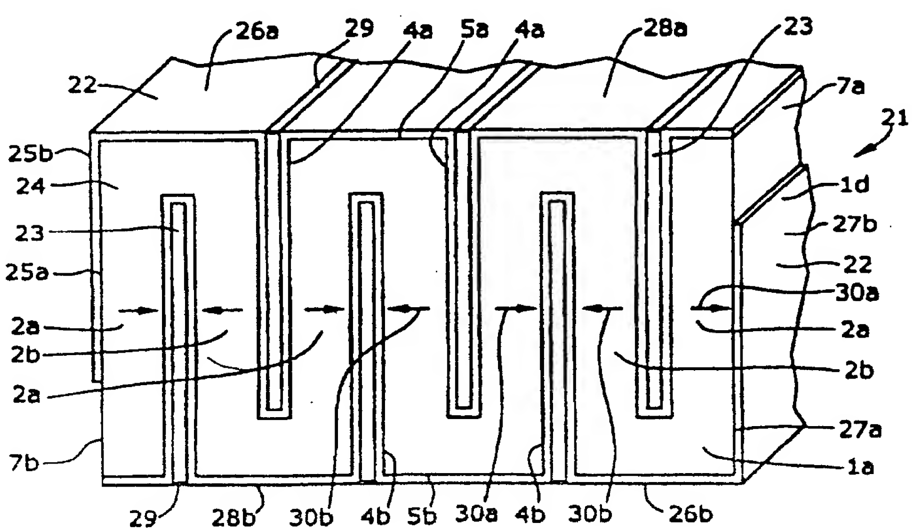

(57) Abstract

A method of fabricating a multilayer piezoelectric transducer. The method involves net-shape molding from a mixture of a piezoelectric or electrostrictive ceramic powder material and an organic binder a unitary piezoelectric or electrostrictive ceramic body. The body (21) includes a top, four sides normal to the top, and a base interconnecting the sides. First and second cavities are molded into at least one side to divide the ceramic body into a plurality of ceramic layers disposed generally parallel to the top. The first cavities alternate with the second cavities in the ceramic body. Each ceramic layer except an uppermost and a lowermost ceramic layer is joined at one edge to one ceramic layer adjacent thereto by a first ceramic bridge and at the same or a different edge to another ceramic layer adjacent thereto by a second ceramic bridge.

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MULTILAYER PIEZOELECTRIC CERAMIC TRANSDUCER AND FABRICATION METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is related to U.S. Patent Applications Nos. [Attorney's Docket Nos. MSI1519 and MSI1554], both filed on even date herewith. Application [MSI1554] is incorporated herein by reference.

GOVERNMENT CONTRACT INFORMATION

The Government of the United States of America has certain rights in this invention pursuant to Contract No. N00014-95-C-0358 awarded by or for the U.S. Department of Defense.

BACKGROUND OF THE INVENTION

The present invention relates to piezoelectric transducers and particularly to transducers having multiple ceramic layers. Such transducers are useful, individually or grouped in an array, for applications including, but not limited to, positioning, sensing, vibration generation and detection, active vibration control, non-destructive evaluation and diagnostics, underwater acoustic imaging, and medical diagnostic ultrasound.

Multilayer transducers are those having multiple layers of laminated piezoelectric or electrostrictive ceramic material separated by electrode material. The advantages offered by such multilayer devices include increased displacement and lower voltage operation in actuators and low electrical impedance in resonant transducer devices.

The transducer is the limiting factor determining the performance quality of many present-day transducer-dependent devices. The number of ceramic layers in each multilayer transducer has been limited by current fabrication technology and the need to interleave the piezoelectric of each

transducer with electrode layers prior to the sintering process. In some devices, a transducer less than 0.2 × 0.2 mm, and even as small as about 25 - 400 μm square in cross section would be highly desirable, further complicating the fabrication process.

Presently available multilayer piezoelectric ceramic transducers are expensive to fabricate and are not sufficiently reliable for many applications. State of the art multilayer transducers are fabricated by stacking pre-metallized green ceramic layers using various processes that involve a number of critical laminating and indexing steps. The green ceramic layers typically are made by roll compaction of the ceramic powder or by tape casting mixtures of ceramic powders and liquid organic binder to form thin sheets. After screen printing to apply the electrode patterns, the layers are stacked and laminated together, typically by pressing, and heated to burn away the organic materials before sintering the binder-removed ceramic multilayer stack.

This process presents problems with indexing and stacking faults and bond delamination. Additionally, the number of ceramic layers of the multilayer transducer is limited by the number of ceramic layers that can practically be laminated and by the binder burn-out problems associated with the current roll compaction or tape casting ceramic layer fabrication methods.

Another disadvantage of the stacking methods described above is that, to achieve the maximum benefit from the multilayer configuration, thin ceramic layers (typically about 10 - 1000 μm thick) are desired. For a large transducer, the stacking of many layers is therefore required to achieve the desired overall transducer length dimension, exacerbating the problems of indexing and stacking faults, bond delamination, and reliability. Currently, to achieve a higher number of layers, individual prefired transducer stacks are bonded to one another in an additional process

step, significantly affecting reliability and fabrication cost.

All of these methods usually require that the screen printed electrode be fabricated from costly platinum, because the ceramic and electrode layers must be assembled into a stack before the ceramic is fired and only platinum will withstand the high temperature necessary for sintering the ceramic after such assembly. The requirement for such platinum internal electrode layers is a major contributor to the high cost of currently available multilayer transducers.

One known multilayer ceramic structure, a capacitor, is built up from stacked and laminated green ceramic tapes produced by conventional tape casting techniques. Planar internal cavities are produced within this structure in a multilayer configuration by screen printing the tapes prior to lamination with pads of binder-rich ceramic ink. After lamination, the tape casting binder and the binder-rich ink are burned away and the parts are sintered, yielding a multilayer structure of dense ceramic layers separated by porous planar ceramic layers in the pattern of the desired interdigitated internal electrodes. The internal electrodes are then formed by back-filling these internal porous layers with molten metal or other electrically conductive material. This process, however, is still hampered by the limitations imposed by the above-described indexing and stacking faults. Also, the number of ceramic layers of the multilayer structure is still limited by the number of ceramic layers that can practically be laminated and by the binder burn-out problems associated with current tape casting and roll compaction ceramic layer fabrication methods.

Accordingly, it is an object of the present invention to provide a multilayer piezoelectric ceramic transducer which overcomes the disadvantages of the prior art.

It is another object of the invention to provide a multilayer transducer having low electrical impedance and

low drive voltage which can be more economically fabricated than those found in the prior art.

It is yet another object of the invention to provide net-shape forming techniques for readily and economically fabricating the multilayer transducer.

It is still another object of the invention to provide a net-shape formed multilayer transducer exhibiting lower stiffness and lower acoustic impedance than the bulk piezoelectric or electrostrictive ceramic materials or prior art piezoelectric or electrostrictive transducers.

SUMMARY OF THE INVENTION

In accordance with these objects, in one aspect the invention is a method of fabricating a multilayer piezoelectric transducer. The method involves net-shape molding from a mixture of a piezoelectric or electrostrictive ceramic powder material and an organic binder a unitary piezoelectric or electrostrictive ceramic body. The body includes a top, four sides normal to the top, and a base interconnecting the sides. First and second cavities are molded into at least one side to divide the ceramic body into a plurality of ceramic layers disposed generally parallel to the top. The first cavities alternate with the second cavities in the ceramic body. Each ceramic layer except an uppermost and a lowermost ceramic layer is joined at one edge to one ceramic layer adjacent thereto by a first ceramic bridge and at the same or a different edge to another ceramic layer adjacent thereto by a second ceramic bridge. The binder is removed from the ceramic body, and the ceramic body is sintered to achieve near-theoretical density. One or more materials are disposed in the first and second cavities to form first and second electrically conductive electrode layers, respectively, each of the electrode layers being bonded to the ceramic layers adjacent thereto. The first electrode layers are electrically interconnected to provide a first set of electrode layers, and the second electrode layers are elec-

trically interconnected to provide a second set of electrode layers alternating with and electrically isolated from the first set electrode layers to form an electroded body. The electroded body is poled to produce the multilayer transducer.

In other aspects, the invention is a net-shape molded ceramic body for fabricating an electronic device. The ceramic body includes a top, four sides generally normal to the top, and a base interconnecting the sides. The body further includes a plurality of ceramic layers including an uppermost ceramic layer, a lowermost ceramic layer and one or more intermediate ceramic layers all disposed generally parallel to the top. Each intermediate ceramic layer is joined at one edge to a ceramic layers adjacent thereto by a first ceramic bridge. In one aspect, Each intermediate ceramic layer is also joined at an opposite edge to another ceramic layers adjacent thereto by a second ceramic bridge, leaving cavities between the ceramic layers and providing a serpentine-shaped cross-section to the ceramic body. In another aspect, each intermediate ceramic layer is joined at the same edge to another ceramic layers adjacent thereto by a second ceramic bridge, leaving cavities between the ceramic layers and providing a comb-shaped cross-section to the ceramic body.

In another aspect, the invention is a multilayer piezoelectric ceramic transducer. The transducer includes a net-shape molded unitary piezoelectric or electrostrictive ceramic body comprising a top, four sides generally normal to the top, and a base interconnecting the sides. The transducer further includes a plurality of ceramic layers including an uppermost ceramic layer, a lowermost ceramic layer and one or more intermediate ceramic layers all disposed generally parallel to the top. Each intermediate ceramic layer is joined at one edge to a ceramic layer adjacent thereto by a first ceramic bridge and at the same or a different edge to another ceramic layers adjacent thereto by

a second ceramic bridge. The transducer has a plurality of electrode layers including an electrode layer between and bonded to each adjacent pair of ceramic layers, the electrode layers nearly completely separating the adjacent pair of ceramic layers. The electrode layers are divided into a first set of electrode layers and a second set of electrode layers, the first set electrode layers alternating with the second set electrode layers in the body. The electrode layers of each set are electrically interconnected with one another and are electrically isolated from the electrode layers of the other set in the body.

In yet another aspect, the invention is molding apparatus for net shape molding of a ceramic blank for fabrication of a multilayer transducer from a mixture of a piezoelectric or electrostrictive ceramic and a thermosetting or thermoplastic organic binder. The apparatus includes a mold having a generally rectangular bottom, two generally rectangular side walls generally normal to and extending upwardly from the bottom at opposite sides thereof, two end walls interconnecting the side walls and generally normal to the bottom and the side walls and extending upwardly from the bottom at opposite sides thereof, and a top generally parallel to the bottom and interconnecting the side walls and the end walls to form a closed rectangular box. The top, bottom, side walls and end walls define a mold cavity. The mold is divided into an upper and a lower mold half which may be brought together to form the mold. The mold bottom has a plurality of slot-shaped openings therein, the bottom slot-shaped openings extending across the bottom to or nearly to the side walls. A plurality of parallel first blade inserts is fitted closely within the slot-shaped openings in the bottom and extend into the mold cavity close to the top when the mold halves are brought together. The first blade inserts extend across the bottom to or nearly to the side walls. Optionally, a plurality of second blade inserts, parallel to one another and to the first blade inserts, are

fitted closely within slot-shaped openings in the top, and extend into the mold cavity between the first blade inserts close to the bottom when the mold halves are brought together, such that the first blade inserts and second blade inserts are interdigitated with each other within the mold cavity. The second blade inserts extend across the top to or nearly to the side walls.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the present invention, together with other objects, features, advantages, and capabilities thereof, reference is made to the following Description and appended Claims, together with the Drawing in which:

Figure 1 is a perspective view of a sintered lead zirconate titanate (PZT) ceramic blank used for fabrication of the multilayer piezoelectric ceramic transducer of Figure 3;

Figure 2A is a schematic cross-sectional perspective view of the molding apparatus and green PZT preform of the blank of Figure 1, before molding;

Figure 2B is a schematic cross-sectional elevation view of the molding apparatus and green PZT preform of the blank of Figure 1, after molding;

Figure 3 is a perspective view of a multilayer ceramic transducer in accordance with one embodiment of the present invention;

Figure 4 is a photomicrograph of a portion of a sintered lead zirconate titanate (PZT) ceramic blank used for fabrication of a multilayer transducer similar to that shown in Figure 3;

Figure 5 is a photomicrograph of a portion of a sintered PZT body, similar to those shown in Figures 3 and 4, after backfilling with a silver-epoxy resin;

Figures 6A and 6B are schematic perspective views of molding apparatus (tooling) for molding a PZT ceramic blank

for fabricating a multilayer ceramic transducer in accordance with another embodiment of the invention;

Figure 7 is a schematic, cross-sectional, perspective view of a sintered PZT ceramic blank molded in the apparatus shown in Figures 6A and 6B, showing two of the internal cavities molded by the tooling shown in Figure 6A;

Figure 8 is an exploded perspective view of a multilayer ceramic transducer fabricated by metal-coating and backfilling the internal cavities of the blank shown in Figure 7, showing the configuration of the electrodes at various y-z planes within the transducer;

Figure 9 is a graph of resonance data for a multilayer transducer in accordance with another embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The description below of various illustrative embodiments shown in the Drawings is not intended to limit the scope of the present invention, but merely to be illustrative and representative thereof.

In its several embodiments, the multilayer piezoelectric ceramic transducer described herein is fabricated from a multilayer ceramic blank net-shape molded from a piezoelectric or electrostrictive ceramic. Examples of such piezoelectric or electrostrictive ceramics are well known in the art, and include, but are not limited to, lead zirconate titanate (PZT); lead magnesium niobate; a titanate, zirconate, or niobate of lead, barium, bismuth, or strontium; or a derivative of any of these. As used herein, the term "piezoelectric ceramic" refers to any of these ceramic materials.

Figure 1 illustrates an example of such a blank, showing sintered PZT piezoelectric ceramic blank 1a of width W, height H, and length L (in the x, y, and z dimensions, respectively, as shown in Figure 1). Blank 1a has multiple parallel ceramic layers 2 of thickness T, interconnected by

inactive bridging portions 3a and 3b of thickness I at alternating edges of layers 2, forming a ceramic body of serpentine cross-section. Alternating gaps or cavities 4a and 4b of thickness G entering blank 1a from opposite side surfaces 5a and 5b of blank 1a are interposed between layers 2 to separate the layers.

Blank 1a is shown as having seven ceramic layers 2. However the layers in a multilayer transducer may vary from two to 1000, or even several thousand layers, while the thickness of each ceramic layer is typically about 10 - 10,000 μm and the length (z-dimension) of the transducer is typically about 0.1 - 1000 mm, depending on the application for which the transducer is designed. The method described herein makes possible the net-shape molding of a transducer having several thousand, e.g., 10,000 thin layers, each being, e.g., as thin as about 20 μm. Cavities 4a and 4b define the thickness of the electrode layers in the finished transducer, typically 20 - 500 μm.

If desired, the outer dimensions, i.e., width W and length Z of sintered blank 1a may be molded slightly oversize so that the width and length may be modified after sintering and electroding to fine-tune the device to a preselected resonance mode. Also if desired, length Z of sintered blank 1a may be sufficiently large to provide two or more individual transducers, the blank being cut or "diced out" at a bridge 3a or 3b (as at cut 6a) before or after the electroding and/or poling steps described below. Also, conveniently, blank 1a may be of sufficient depth Y to provide two or more transducers, the individual transducers typically being "diced out" from one another (as at cuts 6b), this separation normally being performed at a later stage in the fabrication process, as described further below. However, large blanks having very many layers normally are molded individually.

Figures 2A and 2B illustrate net-shape fabrication of the ceramic blank shown in Figure 1. As shown in Figure 2A,

molding apparatus, or tooling, 8 includes upper and lower mold halves 8a and 8b, respectively. For compression molding, mold halves 8a and 8b are heated by means well known in the art for heating molding apparatus. For injection molding, the molding apparatus includes a gate (not shown), as is well known in the art, for filling the mold. Each of mold halves 8a and 8b has a number of longitudinal blade inserts 9a and 9b, respectively, separating longitudinal cavities 10a and 10b, respectively. As shown in Figure 2B, blade inserts 9a and 9b are disposed to alternate in an interdigital pattern within the closed mold to define a mold cavity which is the negative of the desired blank, i.e., serpentine, multilayered green blank 1c. Conveniently, blade inserts 9a and 9b may be retractable for ease of removal of the blank after molding and cooling. Alternatively, the blade inserts may be fixed within the mold cavity. Also alternatively, both the blade inserts and longitudinal cavities 10a and 10b may be provided by removable and replaceable inserts set into each mold half to define different mold cavity shapes for different electrode spacings and electrode and ceramic layer thicknesses. Thus, a set of differently sized and shaped blade inserts may be used to fabricate a variety of different molded ceramic blanks.

In one exemplary method, a ceramic blank is compression molded by placing green preform 1b between mold halves 8a and 8b. Preform 1b is fabricated from a PZT-binder mixture of a PZT piezoelectric ceramic powder mixed with a thermosetting or thermoplastic organic binder, e.g., a wax. The temperature of apparatus 8 should be slightly greater than the softening temperature of the PZT-binder mixture. As heated mold halves 8a and 8b are brought together, as illustrated by arrows 11a and 11b of Figure 2A, with pressure sufficient to deform preform 1b at the selected mold temperature, heated blade inserts 9a and 9b penetrate into ceramic preform 1b. The displaced material of preform 1b flows into

longitudinal cavities 10a and 10b forming prefired ceramic green body 1c, as shown in Figure 2B.

In another exemplary method, blank 1a is fabricated by injection molding a hot PZT-binder mixture into chilled, closed mold 8 (the mold being cooled to a temperature sufficient to solidify the mixture) to form prefired green body 1c. This molding method is performed in a manner similar to that described for injection molding of piezoelectric ceramic bodies in U.S. Patent No. 5,340,510, incorporated herein by reference.

In either method, after molding, cooling and, e.g., retracting blade inserts 9a and 9b from the mold cavity, green body 1c is removed from the mold. The binder is removed from blank 1c by slow heating and the part is sintered at a temperature and for a time sufficient to densify the blank to near (at least 93% of) theoretical density to form sintered blank 1a described above. Both the binder removal and sintering processes are known in the art. Blank 1a then is prepared for use in a multilayer piezoelectric ceramic transducer as described below.

Figure 3 illustrates individual electroded transducer 21, fabricated from sintered serpentine blank 1a of Figure 1. The entire surface of blank 1a is plated or coated with thin layer 22 of any conventional electrically conducting material. For example a metal such as nickel, silver, or gold may be applied by any suitable conventional process such as vapor metallization, sputtering, or electroless plating. Layer 22 may be, if desired, sufficiently thin to avoid bridging of the layer across gaps 23 in slits or cavities 4a and 4b between ceramic layers 2a and 2b. Alternatively, longitudinal cavities 4a and 4b may be backfilled with the conductive material used for the coating, or may be backfilled with another conductive material, as described below. Excess plating is removed from side surface 24 and the side surface opposite thereto, and from a small portion of each of blank top 27a and blank base 25a,

as uncoated strips 7a and 7b, respectively. (Hereinafter, both side surfaces will be referred to as side surfaces 24.) Alternatively, side surfaces 24 and uncoated strips 7a and 7b may be masked during plating. (If blank 1a has been diced to divide the blank into two or more devices, as described above, at least some of this masking or plating removal will be unnecessary.)

Thus conductive layer 22 is divided into two continuous electrodes, 26a and 26b, electrically isolated from one another by uncoated strips 7a and 7b and side surfaces 24, to form electroded blank 1d. As shown in Figure 3, electrode 26b extends across top surface 27 of electroded blank 1d, down one electroded side 28b, and into longitudinal cavities 4b. Electrode 26a extends across base 25a of electroded blank 1d, up other electroded side 28a, and into longitudinal cavities 4a.

It is preferred that gaps 23 between plated surfaces in cavities 4a and 4b be filled with a suitable electrically conductive or non-conductive filler material, as filled portions 29, to improve mechanical integrity and increase ruggedness of the device. If cavities 4a and 4b are uncoated, an electrically conductive filler material should be selected to provide a similar improvement in mechanical integrity and ruggedness. The filler may be selected to be rigid or compliant to increase or decrease the stiffness of the device to a desired level. The more compliant the filler material, the more the filler will internally absorb acoustic vibration in the device, lowering acoustic impedance. Preferably, the filler material in the cavities or gaps will make a strong bond with the coated or uncoated surfaces of the ceramic layers. A conventional bonding or adhesion agent may be applied to the gap surfaces for this purpose. Examples of suitable non-conductive rigid fillers include thermosetting or thermoplastic polymer resins such as polyurethanes and epoxy resin materials. Examples of suitable electrically conductive rigid or semi-rigid materi-

als include composites of metal particles and polymer resins such as a nickel-, gold-, or silver-epoxy resin, or metals such as nickel, gold, or silver, or conductive glass frits such as a mixture of glass frit and silver powder. Suitable compliant materials include rubbers and other compliant polymer resins, which may be used in their non-conductive form or may be mixed with metal particles to render them conductive. For example, rubber as a filler material provides high compliance, while glass frit and metals are highly rigid materials providing low compliance, and epoxy resins have moderate rigidity and provide intermediate compliance. The dimensions and thickness of the ceramic layers and the material and thickness of the material(s) filling the cavities may be selected to suit the electrical and mechanical requirements of a particular application.

Particulate or powdered materials or mixtures, e.g., a silver-epoxy resin material, may be diluted with a conventional solvent to produce a flowable liquid filler for penetration into the cavities or gaps. Alternatively, certain materials may be rendered flowable by other means, e.g., thermoplastic polymers may be melted or heat softened, and other polymers may be solvent softened. Complete filling of the uncoated cavities or coated gaps is desired. This may be achieved by eliminating entrapped air with a vacuum atmosphere, then using pressure assisted infiltration.

By connecting electrodes 26a and 26b to a power source and to ground, electroded blank 1d may be poled, in a conventional manner, e.g., in the poling directions indicated by arrows 30a and 30b, i.e., in a d_{33} multilayer configuration. If electroded blank 1d has not, as yet, been separated into individual transducer portions along one or more x-z planes, as described above, this separation, if desired, may be performed after poling. Typically, each individual transducer 21 has a rectangular footprint (in the x-y plane)

of about 0.1 x 0.1 mm to 100 x 100 mm and a length of about 0.2 - 1000 mm.

In operation, transducer 21 may be activated by separately connecting electrodes 26a and 26b to a source of electrical power. For positioners or actuators, for example, dc or ac voltage may be used for operation, while for transmitters and resonators ac voltage is preferred. The transducer may also be used without applied voltage for sensing applications.

Figures 4 and 5 illustrate the versatility of the net-shape molding method described above. Figure 4 is a photomicrograph of an actual net-shape molded and sintered piezoelectric PZT ceramic blank similar to that shown in Figure 1, while Figure 5 is a photomicrograph of an actual electroded blank 1d similar to that shown in Figure 3. In Figure 4, the thickness of the ceramic layers is less than that of the cavities between ceramic layers; the ceramic layers are about 180 μm thick, while the cavities are about 240 μm thick. Conversely, Figure 5 shows ceramic layers having a thickness greater than that of the cavities between ceramic layers; the ceramic layers are about 345 μm thick, while the cavities are about 41 μm thick. The blanks of Figures 4 and 5 have heights H of about 910 μm and about 735 μm, respectively, and each include about 10 ceramic layers. Each blank has an as-molded width W of about 0.5 inches, and may be cut to provide a desired width. The cavities of the blank shown in Figure 5 are filled with a silver-epoxy resin material.

Another exemplary embodiment of the multilayer piezoelectric ceramic transducer in accordance with the invention includes electrodes which may be connected to an electrical circuit from a single side of the transducer. Molding apparatus, or tooling, for fabricating this transducer is illustrated in Figures 6A and 6B. Mold 40 includes upper and lower mold halves 40a and 40b, respectively, each including a base, 41a and 41b, respectively, end walls 42a and

42b, respectively, and side walls 43a and 43b, respectively. (Only the rear side wall of each mold half is shown, for clarity of illustration.)

Base 41b of lower mold half 40b includes at least four slots 41c into which are inserted at least two of each of first and second mold blade inserts, 44a and 44b, respectively, as shown in Figure 6A. Each of blade inserts 44a includes a lug 45a projecting upwardly from its top edge 46a, while each of blade inserts 44b includes a lug 45b projecting upwardly from its top edge 46b. Optionally, blade insert 44a may include one or more slits 47a, while blade insert 44b may include one or more slits 47b, slits 47a and 47b extending from the top edge downwardly into body 48a or 48b, respectively, of each blade insert. Blade inserts 44a and 44b are inserted into slots 41c of lower mold half base 41b in an alternating arrangement in which each of blade inserts 44a is between two blade inserts 44b and vice versa, except for the blade closest to each of end walls 42 of lower mold half 40b. When the blade inserts are positioned in lower mold half base 41b, lugs 45a are aligned with one another and lugs 45b are aligned with one another but not with lugs 45a. Conveniently, lugs 45a and 45b are aligned along parallel lines. Also, slits 47a and 47b do not extend to base 41b, but leave a solid portion 49a or 49b, respectively, above base 41b when the blade inserts are in position in the base, as shown in Figure 6A.

As shown in Figure 6B, blade inserts 44a and 44b may be withdrawn from mold 40, for ease of removal of a molded transducer blank. Alternatively, the blade inserts may be fixed within the mold cavity. Also alternatively, both the blade inserts may be provided by removable and replaceable mold inserts set into the lower mold half to define different mold cavity shapes for different electrode spacings and electrode and ceramic layer thicknesses. Thus, a set of differently sized and shaped blade inserts may be used to fabricate a variety of different molded ceramic blanks.

As described above for the molding apparatus shown in Figures 2A and 2B, mold halves 40a and 40b are heated for compression molding by means well known in the art for heating molding apparatus. For injection molding, the molding apparatus includes a gate (not shown), as is well known in the art, for filling the mold. Molding of a ceramic blank using mold 40 is performed by compression or injection molding a piezoelectric or electrostrictive material in a manner similar to that described for mold 8 of Figures 2A and 2B.

An exemplary molded part is illustrated in Figure 7. Molded PZT ceramic green body 50 is the negative of the mold cavity of mold 40. Green body 50 includes upper and lower sides 51a and 51b, respectively, front and rear sides 52, end 53a, and base 53b. Cavities 54a and 54b, corresponding to blade inserts 44a and 44b, respectively, extend into green body 50. (The internal shape of one of each of cavities 54a and 54b is shown, for clarity of illustration.) Extensions 55a and 55b of cavities 54a and 54b, respectively, extend upwardly into green body 50 beyond cavity edges 56a and 56b, respectively, at positions corresponding to those of lugs 45a and 45b of mold 50. Ceramic bridges 57a and 57b interrupt the continuity of cavities 54a and 54b, respectively, at positions corresponding to slits 47a and 47b, respectively, but cavities 54a and 54b extend across the width of green body 50 near lower side 51b, corresponding to blade insert solid portions 49a and 49b.

Green body 50 is binder-removed and sintered to near-theoretical density, as described above. Cavities 54a and 54b are vacuum infiltrated with, e.g., silver-epoxy resin conductive material, also as described above, to completely backfill the cavities and cavity extensions with the conductive material. Alternatively, cavities 54a and 54b may be plated and backfilled with a conductive or non-conductive material, also as described above.

The resulting filled blank is lapped at upper side 51a to expose cavity extensions 55a and 55b and electroded to electrically interconnect alternating electrodes, as shown in Figure 8, and poled as described above to establish d_{33} polarity. Figure 8 is a view of multilayer transducer 60 fabricated from green body 50, sectioned and exploded to show the configuration of electrode layers. Sintered PZT ceramic body 50a provides a matrix in which PZT ceramic layers 61 alternate with electrode layers 62a and 62b. Ceramic body 50a is shown in reverse relative to green body 50, i.e., with base 53b to the right, to show one alternative for electroding the transducer, discussed further below.

In this preferred embodiment, electrode layers 62a and 62b extend nearly, but not completely to front and rear sides 52. Electrode layers 62a and 62b are interrupted throughout main portion 63 of ceramic body 50a, but are continuous across lower body portion 64 near lower side 51b. Thus ceramic bridges 65 are provided across each electrode layer to join ceramic layers 61 and to decrease compliance of the electrode layer, but portions 66a and 66b provide electrical continuity for electrode layers 62a and 62b, respectively.

Lugs 67a and 67b extend upwardly from electrode layers 62a and 62b, respectively, through upper ceramic body portion 68. Upper side 51a has been lapped to expose lugs 67a and 67b. Lugs 67a are aligned with one another and are electrically interconnected by conductive strip 68a. Lugs 67b are aligned with one another, but not with lugs 67a, and are electrically interconnected by conductive strip 68b. Optionally, conductive strips may extend to base 53b, as shown in Figure 8, for interconnection to a source of electrical power. Thus, electrode layers 62a are electrically interconnected to one another, and electrode layers 62b are electrically interconnected with one another but electrically isolated from electrode layers 62a to provide an inter-

digitated or alternating arrangement of internal electrode layers similar to that shown in Figure 3, but with both sets of electrode layers electrically connectable from a single side or the base of the transducer.

The following Example is presented to enable those skilled in the art to more clearly understand and practice the present invention. This Example should not be considered as a limitation upon the scope of the present invention, but merely as being illustrative and representative thereof.

EXAMPLE

A set of transducer dimensions was chosen to test the performance of the multilayer transducer. Ceramic blanks were injection molded, as described above, from a piezoelectrically-soft lead zirconate titanate ceramic (PZT-5H), hereinafter designated PZT. After molding and conventional binder removal, the green PZT blanks were sintered in a conventional manner in a lead-controlled atmosphere. The sintered dimensions (see Figure 1) of the blanks were: $H = 800\ \mu m$, $T = 345\ \mu m$, $G = 41\ \mu m$, $I = 140\ \mu m$. The blanks were molded oversized in width and length so that their dimensions could be modified to clearly delineate and separate individual resonance modes. The final widths and lengths of the devices are given in Table 1.

The blanks were thoroughly cleaned in an ultrasonic bath. Internal electrodes were applied to the uncoated ceramic blanks by infiltrating the cavities with a silver-epoxy resin in a sealed chamber adapted to permit evacuation and pressurization of the atmosphere within the chamber. The silver-epoxy resin was de-aired and sufficiently diluted with toluene to be flowable at room temperature. The chamber was evacuated to remove air from the cavities, the silver-epoxy resin was applied to one side of the blank (as side 5a in Figure 1), to seal off the serpentine shaped sides, then air at under 1 MPa pressure was introduced into

the chamber to assist infiltration. The silver-epoxy resin material filling the cavities of one side was cured at 60°C for 4 hours and lapped flat. The process was then repeated to infiltrate the cavities of the opposite side of the blank in the same manner. Complete infiltration of the cavities was achieved, as shown in Figure 5. (Using this method complete penetration of the silver-epoxy resin material to the bottom of the cavities has been achieved in cavities as small as 35 μm wide.)

After infiltration, individual sample devices were cut from the oversized blanks using a low-speed diamond saw. The dimensions of these samples are given in Table 1. Silver paint was applied to the lapped surfaces of each sample for electrical connection of the electrode layers of each side. The samples were poled in a d_{33} multilayer configuration at 1.1 kV/mm and room temperature. After poling, resonance curves were obtained using a Hewlett Packard Model HP4194A impedance analyzer. The results showed that bond disturbances between the ceramic and electrode layers had occurred in Samples 1 and 2. More careful diamond dicing to cut Sample 3 from the blanks eliminated these bond disturbances, proving that the as-infiltrated electrode layers bonded well to the ceramic layers. Additionally, the poling field on the Samples 3 and 4 was increased to about 2 kV/mm to further ensure complete poling of the internal ceramic layers.

Figure 9 is a graph showing the resonance and impedance at frequencies between 50 kHz and 5 MHz of a sample that was carefully diced to minimize bond disruption. The resonances corresponding to the individual layers are diffuse, the width mode resonance (corresponding to the width W) is clearly seen in the upper peak at about 1.4 MHz, and the length mode resonance (corresponding to the total stack length L) is visible in the lower small peak at about 200 kHz, showing good mechanical integrity of the ceramic-electrode bonds.

The measured width and height resonances were correlated with the sample dimensions, as shown in Table 1. These measured resonant frequencies were compared in Table 1 with the corresponding frequencies calculated for monolithic PZT-5H ceramic transducers of equivalent dimensions. The length, width, and height mode resonances of four multilayer transducer samples were calculated from the following equations: $N_3 = f_3L$, $N_1 = f_1W$, and $N_1 = f_1H$. For PZT monolithic ceramic, the frequency constants for these modes are: $N_1 = 1420$ Hz.m and $N_3 = 1930$ Hz.m. Table 1 shows that the height and width mode resonant frequencies for all four samples correspond approximately with those calculated for the monolithic PZT-5H ceramic, but the length mode frequencies are lower than those anticipated for monolithic PZT-5H. This is due to a degree of compliance imparted to the devices by the metal-epoxy resin electrode layers in the length direction. Thus, the compliance of the device in the length dimension can be adjusted to suit the application requirements by varying the internal electrode filler material thickness and stiffness. As mentioned above, rubber as a filler material provides high compliance, while glass frit and metals are highly rigid materials providing low compliance, and epoxy resins have moderate rigidity and provide intermediate compliance.

TABLE 1

Sample	Description	Dimension, mm	f_r, calculated	f_r, measured
1	poor bonding	L = 9.73	198 kHz	not observed
		H = 0.813	1.75 MHz	2.10 MHz
		W = 1.79	793 kHz	866 kHz
2	poor bonding	L = 9.75	198 kHz	not observed
		H = 0.813	1.75 MHz	2.08 MHz
		W = 3.99	356 kHz	396 kHz
3	good bonding (Figure 9)	L = 5.74	336 kHz	209 kHz
		H = 0.84	1.69 MHz	1.74 MHz
		W = 0.99	1.43 MHz	1.42 MHz
4	moderate bonding	L = 5.88	328 kHz	168 kHz
		H = 0.813	1.74 MHz	1.75 MHz
		W = 2.32	612 kHz	670 kHz

The invention described herein presents to the art improved large- or fine-scale multilayer transducers for low or high frequency operation. The transducers exhibit improved electrical and acoustic impedance, improved sensitivity, and fabrication by a net-shape molding process. Such a fabrication makes possible a multilayer transducer having a larger number of layers, with no need for high cost noble metal electrodes. Such transducers are useful, individually or grouped in an array, for applications such as positioning, sensing, vibration generation and detection, active vibration control, mine hunting, undersea surveying and inspection, medical diagnostic imaging, and non-destructive evaluation and diagnostics.

While there has been shown and described what are at present considered the preferred embodiments of the invention, it will be apparent to those skilled in the art that modifications and changes can be made therein without departing from the scope of the present invention as defined by the appended Claims.

WE CLAIM:

1. A method of fabricating a multilayer piezoelectric transducer comprising:

net-shape molding from a mixture of a piezoelectric or electrostrictive ceramic powder material and an organic binder a unitary piezoelectric or electrostrictive ceramic body comprising a top, four sides normal to said top, and a base interconnecting said sides, wherein first and second cavities are molded into at least one of said sides to divide said ceramic body into a plurality of ceramic layers disposed generally parallel to said top, said first cavities alternate with said second cavities in said ceramic body, and each of said ceramic layers except an uppermost and a lowermost of said ceramic layers is joined at one edge to one ceramic layer adjacent thereto by a first ceramic bridge and at the same or a different edge to another ceramic layer adjacent thereto by a second ceramic bridge;

removing said binder from said ceramic body;

sintering said ceramic body to achieve near-theoretical density;

disposing in said first and second cavities one or more materials to form first and second electrically conductive electrode layers, respectively, each of said electrode layers being bonded to the ceramic layers adjacent thereto;

electrically interconnecting said first electrode layers to provide a first set of electrode layers;

electrically interconnecting said second electrode layers to provide a second set of electrode layers alternating with and electrically isolated from said first set electrode layers to form an electroded body; and

poling said electroded body to produce said multilayer transducer.

2. A method in accordance with claim 1 wherein said disposing of said one or more materials in said cavities comprises vacuum infiltrating said cavities to fill said cavities with a rigid or compliant electrically conductive material to form said first and second electrode layers, respectively.

3. A method in accordance with claim 2 wherein said electrically conductive material is selected from the group consisting of metals, conductive glass frits, and composites of metal particles and a polymer resin.

4. A method in accordance with claim 1 wherein said poling results in a d_{33} poling configuration in said transducer.

5. A method in accordance with claim 1 wherein said net-shape molding is performed by injection molding or compression molding.

6. A method in accordance with claim 1 wherein:

said first and second cavities are molded into, respectively, a first of said sides and a second of said sides opposite said first side;

said first cavities alternate with said second cavities in said ceramic body; and

each of said ceramic layers except an uppermost and a lowermost of said layers is joined at one edge to one ceramic layer adjacent thereto by a first ceramic bridge and at an opposite edge to another ceramic layer adjacent thereto by a second ceramic bridge such that said ceramic body has a serpentine cross-section.

7. A method in accordance with claim 6 wherein said interconnecting of said first electrode layers comprises applying an electrically conductive coating to said first side, and said interconnecting of said second electrode layers comprises applying an electrically conductive coating to said second side.

8. A method in accordance with claim 7 wherein said interconnecting of said first electrode layers comprises extending said first side electrically conductive coating to cover said base of said body.

9. A method in accordance with claim 8 wherein said disposing of said one or more materials in said cavities and said electrically interconnecting of said first and second electrode layers comprise:

applying an electrically conductive coating to said ceramic body to cover said base, said first and second sides, and interior surfaces of said first and second cavities; and

removing any portions of said coating required to separate said coating into a first electrode covering said base, said first side, and said first cavity interior surfaces, and a second electrode covering said second side and said second cavity interior surfaces.

10. A method in accordance with claim 9 wherein said electrically conductive coating on said interior surfaces of said first and second cavities defines a gap in each of said first and second cavities; and wherein said method further comprises filling said gaps by vacuum infiltrating said gaps with a conductive or non-conductive, rigid or compliant material to form said first and second electrode layers, respectively.

11. A method in accordance with claim 10 wherein said conductive or non-conductive, rigid or compliant material is selected from the group consisting of metals, conductive glass frits, composites of metal particles and a polymer resin, rubber, and polymer resins.

12. A method in accordance with claim 1 wherein:
said first and second cavities are molded into a first one of said sides, said first cavities alternate with said second cavities in said ceramic body;
said ceramic bridges join said ceramic layers at edges along a second side of said ceramic body opposite said first side such that said ceramic body has a comb-shaped cross-section;
and further comprising:
exposing a portion of each of said electrode layers at said second side of said ceramic body for said electrical interconnecting of said first and second electrode layers to provide said first and second set, respectively, of electrode layers.

13. A method in accordance with claim 12 wherein:
each of said cavities includes an extension extending into the bridge adjacent thereto over a minor portion of the length of said bridge, said first cavity extensions aligning with one another, and said second cavity extensions aligning with one another but not with said first cavity extensions; and
said disposing of said one or materials in said cavities includes disposing of said one or more material in said extensions with said one or more materials to form first and second electrically conductive lugs on said first and second electrode

layers, respectively, said lugs extending into said bridges;

said lapping is performed to expose said lugs; and

said electrical interconnecting of said first and second electrode layers comprises electrically interconnecting said first lugs with one another and said second lugs with one another to provide said first and second set, respectively, of electrode layers.

14. A method in accordance with claim 12 wherein each adjacent pair of said ceramic layers is joined by secondary ceramic bridges extending through said electrode layers.

15. A method in accordance with claim 1 further comprising preselecting, before said molding, a ceramic layer/electrode layer thickness ratio to suit electrical and mechanical requirements of a particular application.

16. A method in accordance with claim 15 further comprising selecting said one or more materials to provide a preselected compliance and acoustic impedance for said transducer.

17. A net-shape molded ceramic body for fabricating an electronic device, said ceramic body comprising a top, four sides generally normal to said top, and a base interconnecting said sides, and further comprising a plurality of ceramic layers including an uppermost ceramic layer, a lowermost ceramic layer and one or more intermediate ceramic layers all disposed generally parallel to said top, wherein each intermediate ceramic layer is joined at one edge to one of said ceramic layers adjacent thereto by a first ceramic bridge and at an opposite edge to another of said ceramic layers adjacent thereto by a second ceramic bridge, leaving

cavities between said ceramic layers and providing a serpentine-shaped cross-section to said ceramic body.

18. A net-shape molded ceramic body for fabricating an electronic device, said ceramic body comprising a top, four sides generally normal to said top, and a base interconnecting said sides, and further comprising a plurality of ceramic layers including an uppermost ceramic layer, a lowermost ceramic layer and one or more intermediate ceramic layers all disposed generally parallel to said top, wherein each intermediate ceramic layer is joined at one edge to one of said ceramic layers adjacent thereto by a first ceramic bridge and to another of said ceramic layers adjacent thereto by a second ceramic bridge, leaving cavities between said ceramic layers and providing a comb-shaped cross-section to said ceramic body.

19. A multilayer piezoelectric ceramic transducer comprising:

a net-shape molded unitary piezoelectric or electrostrictive ceramic body comprising a top, four sides generally normal to said top, and a base interconnecting said sides, and further comprising a plurality of ceramic layers including an uppermost ceramic layer, a lowermost ceramic layer and one or more intermediate ceramic layers all disposed generally parallel to said top, wherein each intermediate ceramic layer is joined at one edge to one of said ceramic layers adjacent thereto by a first ceramic bridge and at the same or a different edge to another of said ceramic layers adjacent thereto by a second ceramic bridge;

a plurality of electrode layers comprising an electrode layer between and bonded to each adjacent pair of said ceramic layers, said electrode layers nearly completely separating said adjacent pair of ceram-

ic layers, wherein said electrode layers are divided into a first set of electrode layers and a second set of electrode layers, said first set electrode layers alternating with said second set electrode layers in said body, and said electrode layers of each of said sets being electrically interconnected with one another and being electrically isolated from said electrode layers of the other of said sets in said body.

20. A multilayer transducer in accordance with claim 19 wherein said ceramic body is formed from a piezoelectric or electrostrictive ceramic material selected from the group consisting of lead zirconate titanates; lead magnesium niobates; titanates of lead, barium, bismuth, and strontium; and derivatives thereof.

21. A multilayer transducer in accordance with claim 19 wherein said plurality of electrode layers further includes a lower electrode layer on said base, and wherein said first set of electrode layers includes said lower electrode layer.

22. A multilayer transducer in accordance with claim 19 wherein said ceramic body is poled in a d_{33} multilayer configuration.

23. A multilayer transducer in accordance with claim 19 wherein said first and second electrode layers extend into said ceramic body from, respectively, a first of said sides and a second of said sides opposite said first side; said first electrode layers alternate with said second electrode layers in said ceramic body; and each of said ceramic layers except an uppermost and a lowermost of said layers is joined at one edge to one ceramic layer adjacent thereto by a first ceramic bridge and at an opposite edge to

another ceramic layer adjacent thereto by a second ceramic bridge such that said ceramic body has a serpentine cross-section.

24. A multilayer transducer in accordance with claim 23 wherein said first electrode layers are interconnected by an electrically conductive coating on said first side, and said second electrode layers are interconnected by an electrically conductive coating on said second side.

25. A multilayer transducer in accordance with claim 24 wherein a first electrically conductive coating on said ceramic body covers said base, said first side, and interfaces between said ceramic layers and said first electrode layers; and a second electrically conductive coating on said ceramic body covers said second sides and interfaces between said ceramic layers and said second electrode layers, said second conductive coating being electrically isolated from said first conductive coating.

26. A multilayer transducer in accordance with claim 25 wherein said first electrically conductive coating defines a gap in each of said first and second electrode layers; and wherein said gaps are filled with a rigid or compliant, conductive or non-conductive material completing said first and second electrode layers, respectively.

27. A multilayer transducer in accordance with claim 26 wherein said rigid or compliant, conductive or non-conductive material is selected from the group consisting of metals, conductive glass frits, composites of metal particles and a polymer resin, rubber, and polymer resins.

28. A multilayer transducer in accordance with claim 19 wherein:

said first and second electrode layers extend into a first one of said sides, said first electrode layers alternating with said second electrode layers in said transducer;

said ceramic bridges join said ceramic layers at edges along a second side of said ceramic body opposite said first side such that said ceramic body has a comb-shaped cross-section; and

said electrode layers are exposed at said second side.

29. A multilayer transducer in accordance with claim 28 wherein:

each of said electrode layers includes a lug comprising an electrically conductive material extending into the bridge adjacent thereto over a minor portion of the length of said bridge, said first lugs aligning with one another, and said second lugs aligning with one another but not with said first lugs;

said lugs of said first and second electrode layers are exposed at said second side; and

said first lugs are electrically interconnected with one another and said second lugs are electrically interconnected with one another to provide said first and second set, respectively, of electrode layers.

30. A multilayer transducer in accordance with claim 19 wherein said said electrode layers are more compliant than said ceramic layers.

31. Molding apparatus for net shape molding of a ceramic blank for fabrication of a multilayer transducer from a mixture of a piezoelectric or electrostrictive ceramic and a thermosetting or thermoplastic organic binder, said apparatus comprising:

a mold having a generally rectangular bottom, two generally rectangular side walls generally normal to and extending upwardly from said bottom at opposite sides thereof, two end walls interconnecting said side walls and generally normal to said bottom and said side walls and extending upwardly from said bottom at opposite sides thereof, and a top generally parallel to said bottom and interconnecting said side walls and said end walls to form a closed rectangular box, said top, said bottom, said side walls and said end walls defining a mold cavity, and said mold being divided into an upper and a lower mold half which may be brought together to form said mold;

said mold bottom having a plurality of slot-shaped openings therein, said bottom slot-shaped openings extending across said bottom to or nearly to said side walls;

a plurality of parallel first blade inserts fitted closely within slot-shaped openings in said bottom and extending into said mold cavity close to said top when said mold halves are brought together; said first blade inserts extending across said bottom to or nearly to said side walls;

optionally, a plurality of second blade inserts parallel to one another and to said first blade inserts, fitted closely within slot-shaped openings in said top, and extending into said mold cavity between said first blade inserts close to said bottom when said mold halves are brought together, such that said first blade inserts and said second

blade inserts are interdigitated with each other within said mold cavity; said second blade inserts extending across said top to or nearly to said side walls.

32. Molding apparatus in accordance with claim 31 including no second slot-shaped openings and no second blade inserts; wherein said first blade inserts are divided into primary and secondary first blade inserts alternating with one another; and said first blade inserts each contact or nearly contact said mold top when said mold halves are brought together.

33. Molding apparatus in accordance with claim 32 wherein said first blade inserts each comprise a lug extending upwardly into said mold cavity to contact or nearly contact said mold top when said mold halves are brought together, said primary blade insert lugs being aligned with one another and said secondary blade insert lugs being aligned with one another but not with said primary blade insert lugs.

34. Molding apparatus in accordance with claim 31 wherein said first blade inserts each include one or more slits extending from a top edge thereof to nearly but not totally reach said mold bottom; and, optionally, said second blade inserts each include one or more slits extending from a bottom edge thereof to nearly but not totally reach said mold top.

35. Molding apparatus in accordance with claim 31 further comprising means for heating said mold to a temperature sufficiently high to soften a preform made from said ceramic-binder mixture; and means for bringing said upper and lower mold halves together with sufficient pressure to cause said softened preform to fill said mold cavity.

36. Molding apparatus in accordance with claim 31 further comprising a gate for filling said mold cavity with said ceramic-binder mixture for injection molding of said ceramic blank.

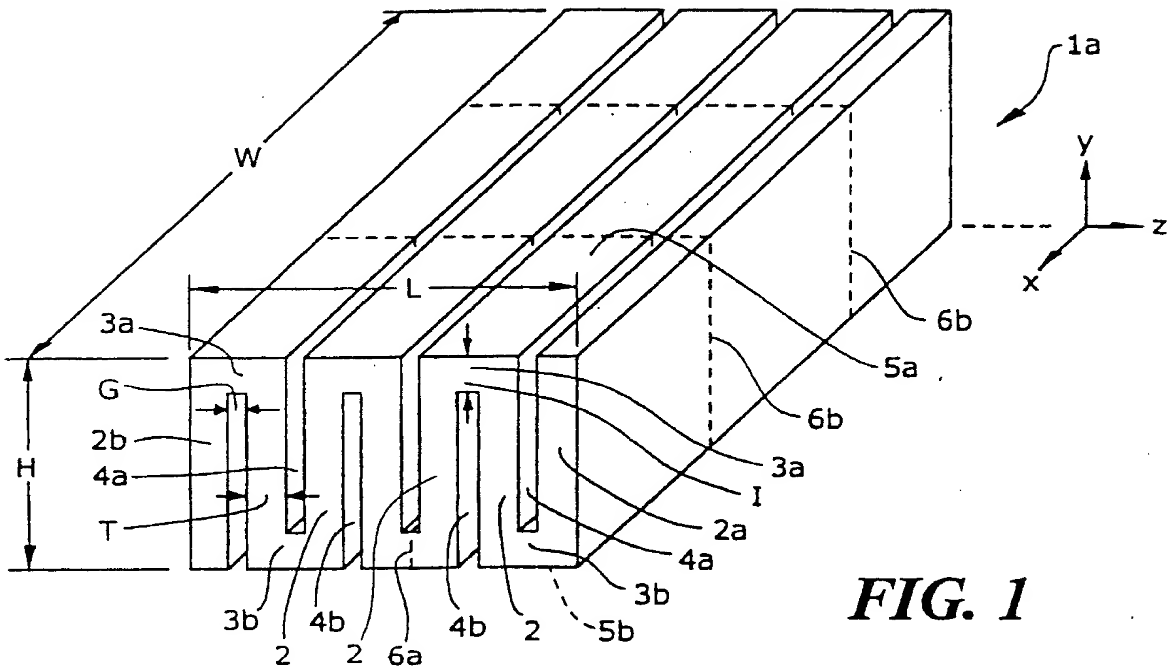


FIG. 1

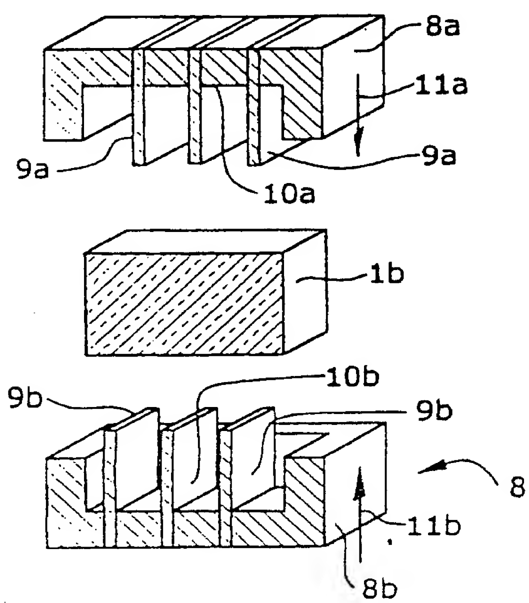


FIG. 2A

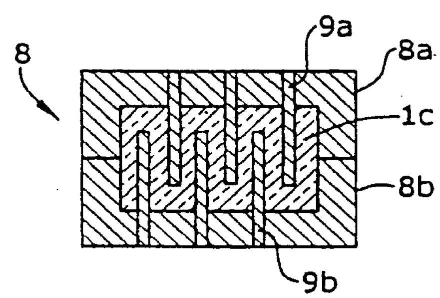
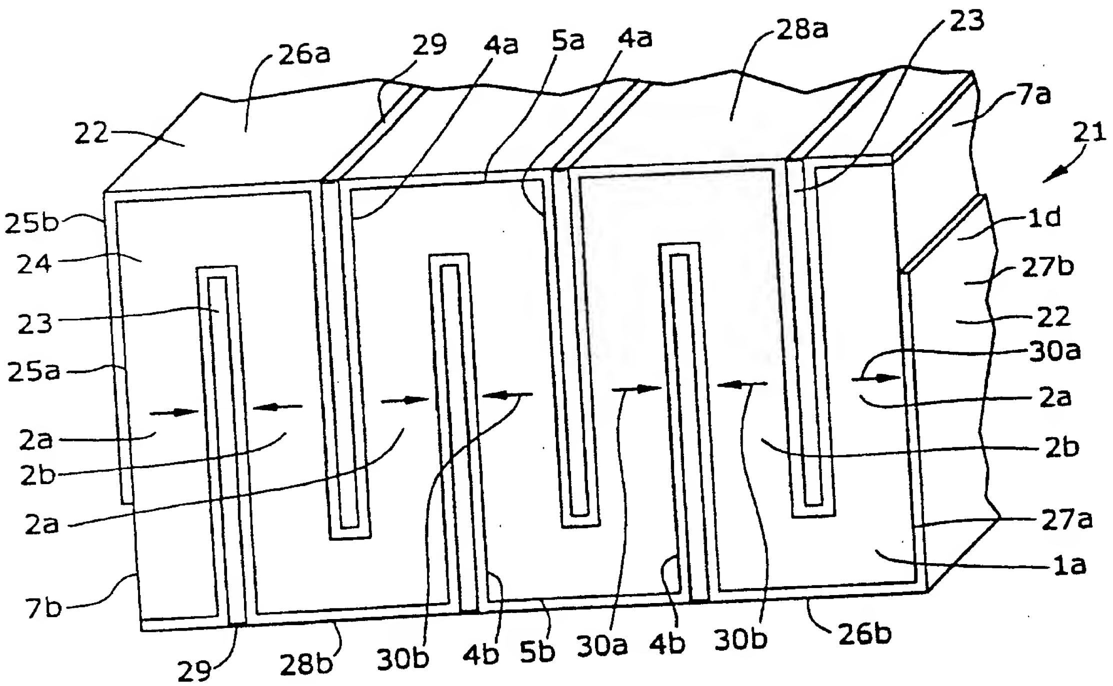


FIG. 2B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1d
27b
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4b
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26b

FIG. 3

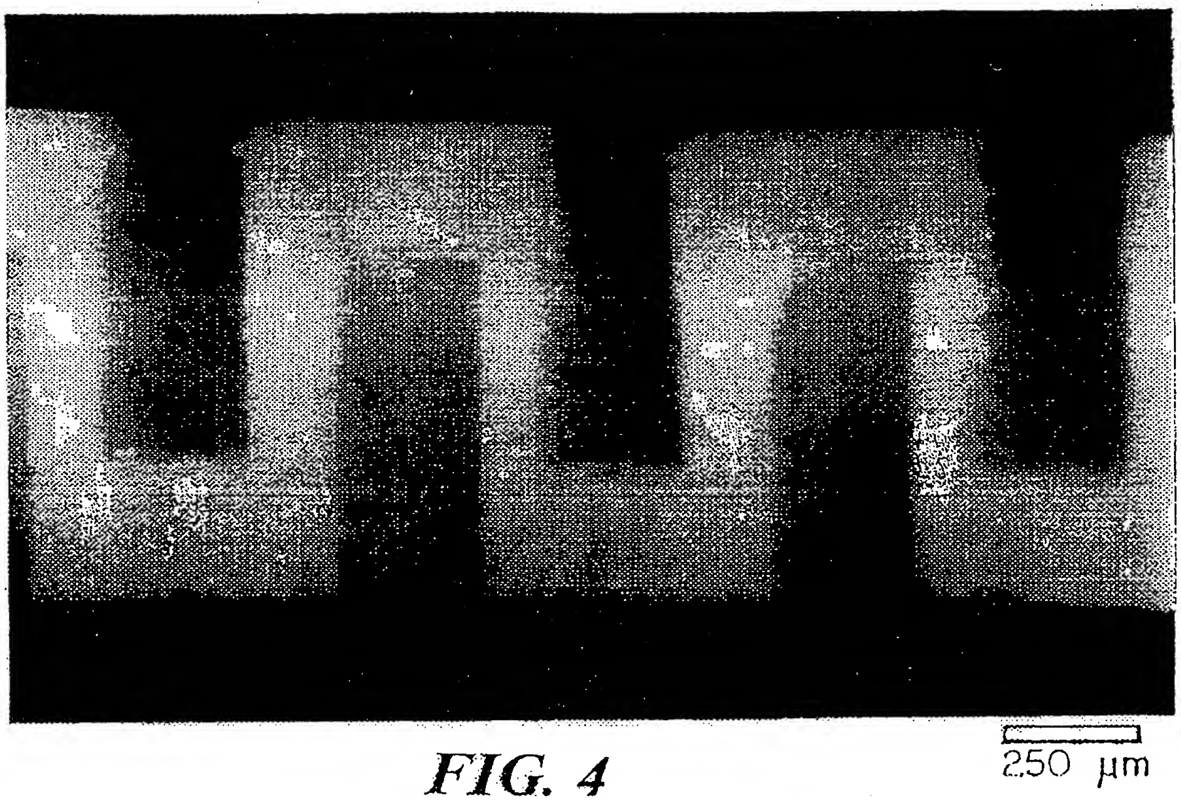

FIG. 4

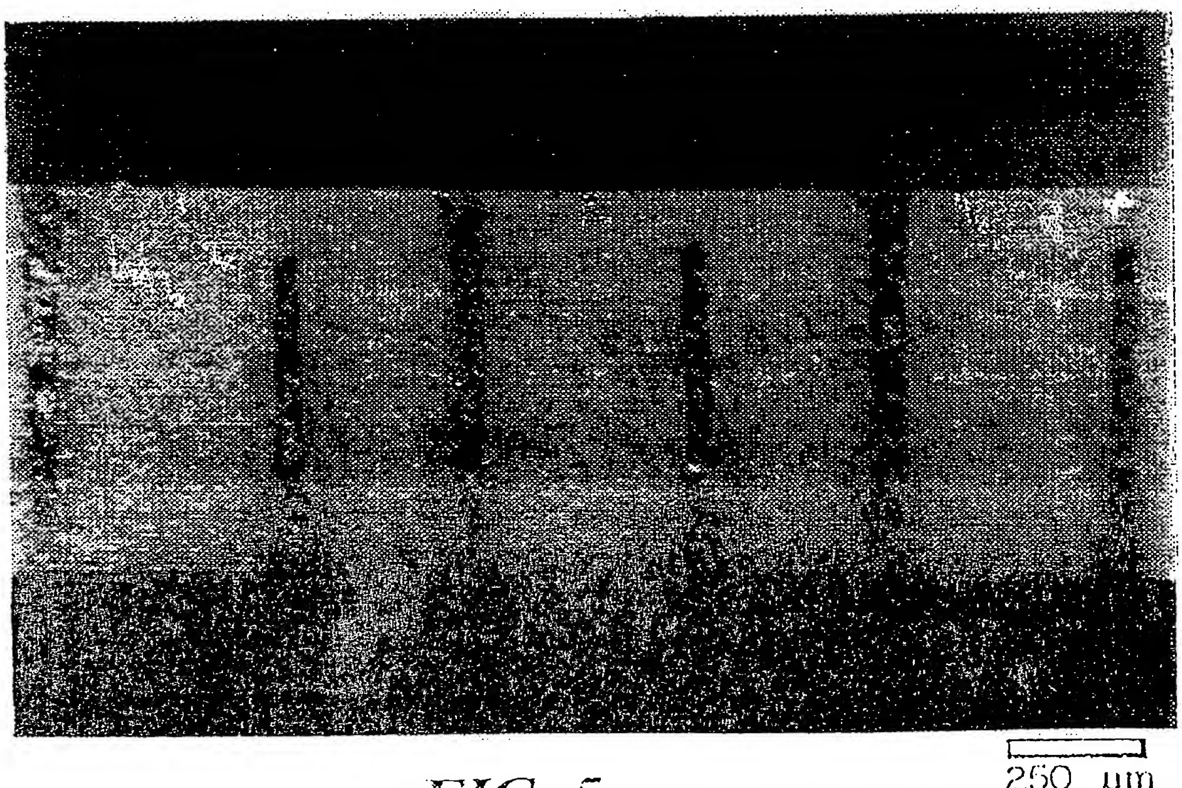

FIG. 5

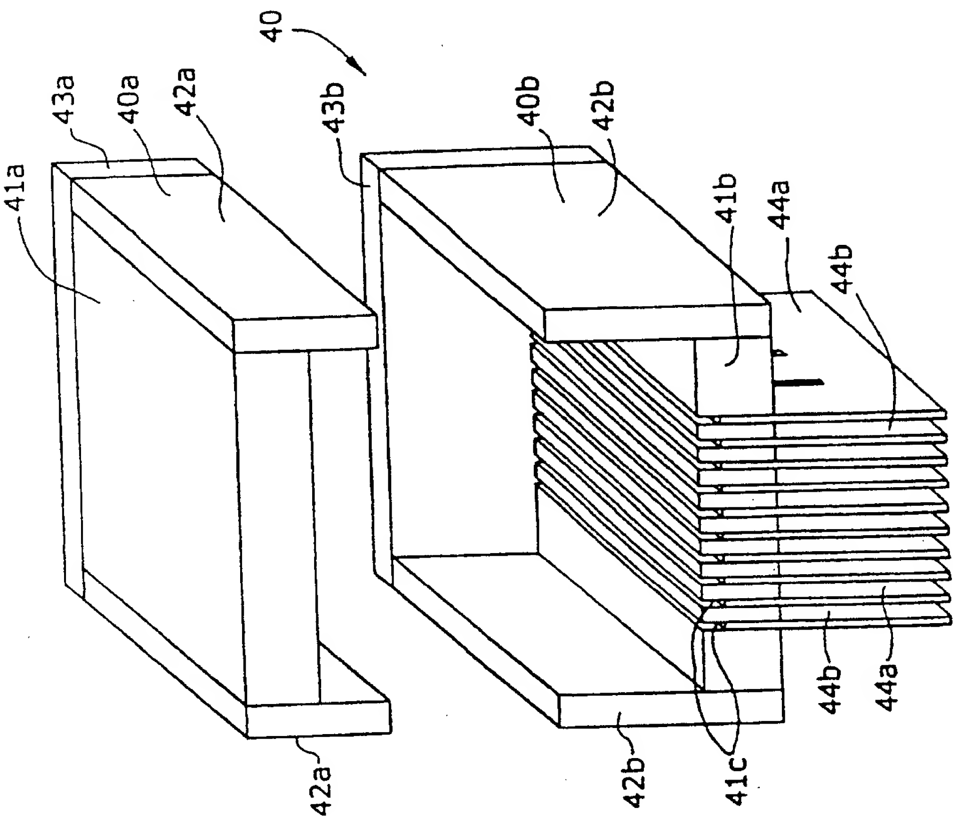
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FIG. 6B

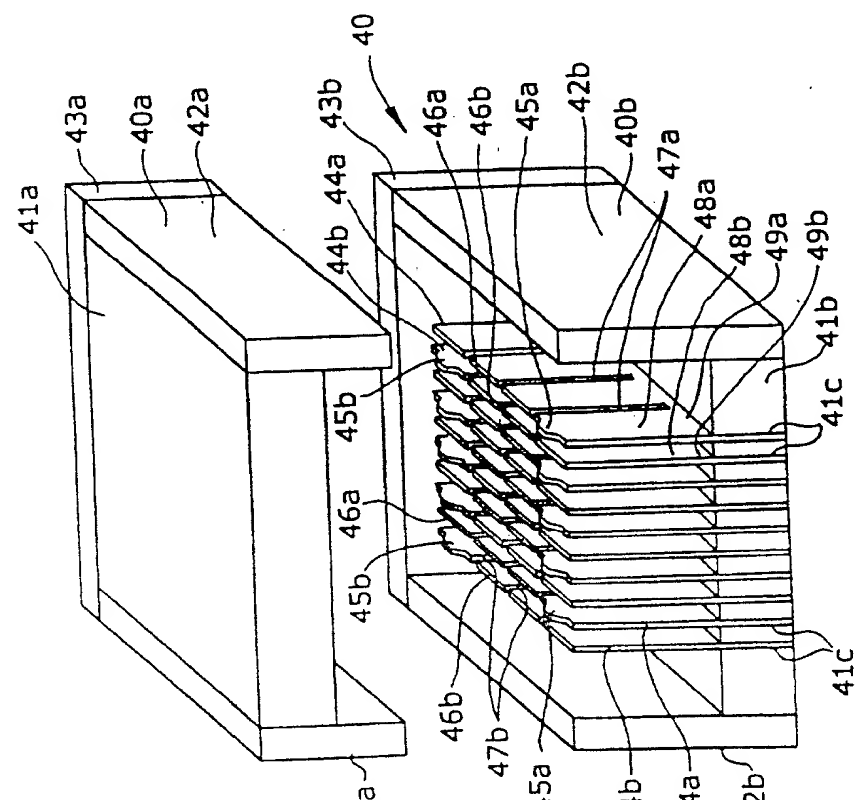
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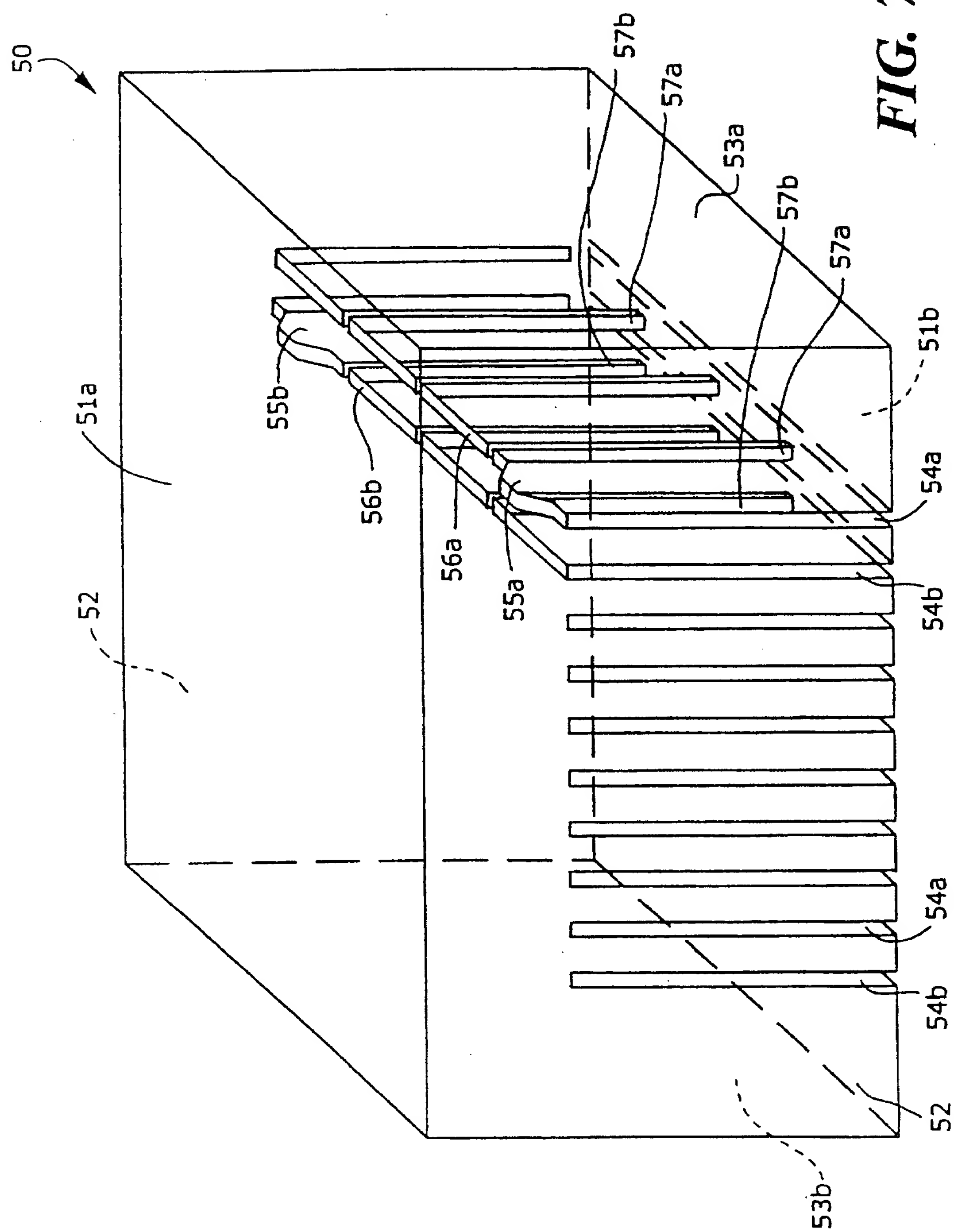
FIG. 6A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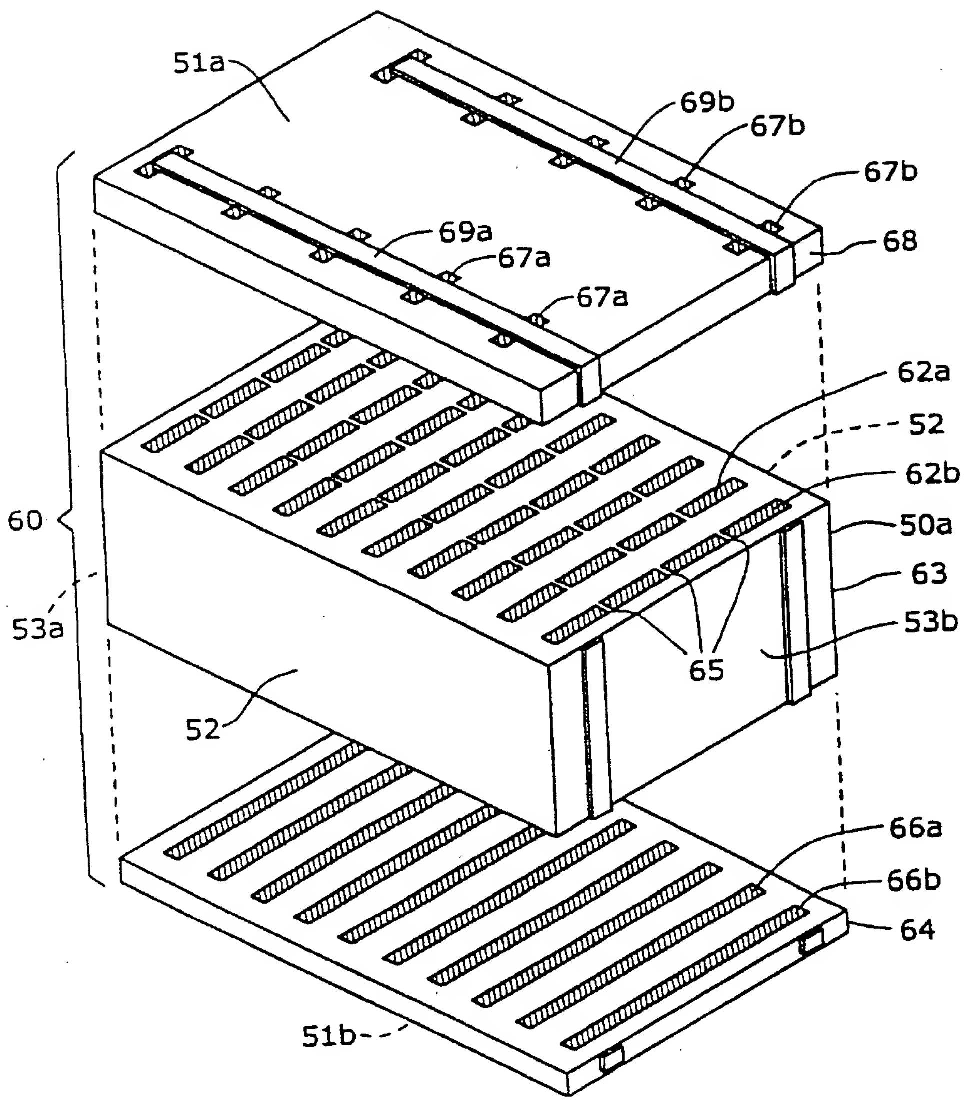
53b

FIG. 7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51b

FIG. 8

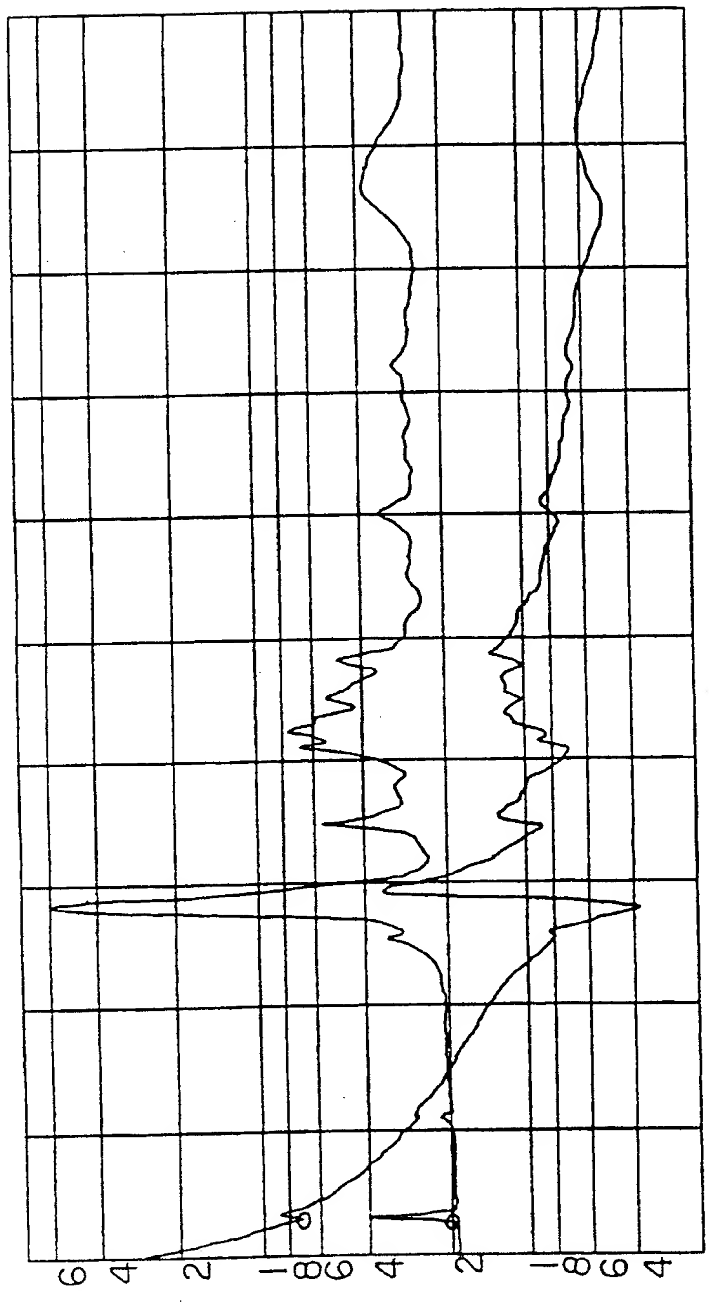

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/13025

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :HO1L 41/08
US CL :310/359
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 310/328, 358, 359, 366-368

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, 5,633,554 A (KAJI) 27 May 1997, see entire document.	1-36
X	US, 5,245,734 A, (ISSARTEL) 21 September 1993, see figs. 1 and 6.	1-36
X	US, 2,497,108 A (WILLIAMS) 14 February 1950, see figs. 7 and 8.	1-36

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 OCTOBER 1997	03 DEC 1997
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer MARK BUDD Telephone No. (703) 308-3929

Form PCT/ISA/210 (second sheet)(July 1992)*